Simulation of gas–solid two-phase flow in the annulus of drilling well

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ABSTRACT

This paper investigates the hydrodynamic behavior of gas–solid two-phase flow in the annular space of an air drilling well under different arrangements by using three-dimensional approach. Two-fluid model is used to solve the governing equations in the Eulerian–Eulerian framework. Effect of eccentricity and drill pipe rotation on the pressure drop, volume fraction and velocity profile are examined. The results are compared with available data in the literature and good agreement is found. The results show that the presence of solid particles in the annulus change the air velocity profile significantly and create two off-center peaks velocity close to the walls instead of one peak velocity in the middle. Eccentricity of drill pipe makes more accumulation of the cuttings in the smaller space of the annulus. Increasing the eccentricity increases pressure drop due to impact of particles with annulus wall and also particles collision with each other. Rotation of the drill pipe shifts maximum air velocity location toward smaller space of the annulus which results more uniform cutting distributions in the annulus and improvement in their transportations. Pressure drop in the annulus increases as eccentricity and rotation of drill pipe increase.

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1. Introduction

Gas–particle flows can be found in different industrial systems. Generally, gas–particle flows can be divided into two sub-classes, namely gas–solid and gas–droplet flows. The main difference between them is lack of mass transfer in the gas–solid compare to gas droplet flow. Some applications of gas–particle flows include cyclone separators and classifiers, pneumatic transport of powder, droplet combustion systems, spray drying and cooling, as well as sandblasting. Another industrial application of gas–solid flows which is the subject of this paper is in air and gas drilling operation. In this operation air or other gases (e.g., nitrogen or natural gas) is used as a circulating fluid instead of mud, which is usually used for drilling operation. The fluid is injected through the center of the drill pipe and back up to the surface through the annular space between the drill pipe and the hole, as shown in Fig. 1. One major purpose of this circulating fluid is the transportation of solid cuttings from the bottom of the hole to the surface (i.e., hole cleaning).

Using gases like air or nitrogen as a circulating fluid in a rotary drilling began in the early fifties. Air drilling has many advantages over mud drilling, such as higher penetration rate, less formation damage, increase in bit life and lower drilling cost. An additional advantage, of importance today, is protection of the environment from drilling mud contamination. Therefore, the use of air as a circulating medium for drilling oil and gas wells is becoming an attractive practice in certain areas. Its application has been increased more since underbalanced drilling (UBD) was introduced to the drilling industry in which the borehole pressure should be held at lower pressure compare to the formation pressure.

Over the past three decades, various mathematical and empirical models have been developed to predict the performance of air and gas drilling operations. Each model is based on a variety of assumptions concerning the interaction of the gas and cuttings in the annulus. The first method proposed for predicting volume requirements in air and gas drilling was presented by Martin (1952, 1953). His predictions were based on the application of the Weymouth formula for horizontal...
Two-fluid model is used for simulation of gas–solid upward flow in the annulus of a well. The governing equations of gas–solid flow are presented in the Eulerian–Eulerian framework in which the particles and gas are viewed as continuous phases. The gas and particles behavior can be predicted by solution of the governing partial differential equations in three-dimensional cylindrical coordinate system. Coordinate system is fixed and particles pass through the fixed control volumes. The governing equations of this model are as follow:

The continuity equation for phase \( q \) is given as follow:

\[
\frac{\partial (\rho_q \dot{V}_q)}{\partial t} + \nabla \cdot (\rho_q \dot{V}_q \rho_q \dot{V}_q) = \sum_{p=1}^{n} \dot{m}_{pq} ,
\]

(1)

where \( \dot{V}_q \) is the velocity of phase \( q \) and \( \dot{m}_{pq} \) characterizes the mass transfer from the \( p \)th to \( q \)th phase. From the mass conservation equation one can obtain

\[
\dot{m}_{pq} = -\dot{m}_{qp} \quad \text{and} \quad \dot{m}_{pp} = 0 .
\]

(2)

The momentum balance for gas phase \( q \) yields

\[
\frac{\partial (\rho_q \dot{V}_q \rho_q \dot{V}_q)}{\partial t} + \nabla \cdot (\rho_q \dot{V}_q \rho_q \dot{V}_q) = -\alpha_q \nabla \rho_p - \nabla \cdot (\rho_q \dot{V}_q \rho_q \dot{V}_q) + \alpha_q \dot{g}_q (\tilde{F}_q + \tilde{F}_{sl,q} + \tilde{F}_{om,q}) ,
\]

(3)

where \( \tilde{F}_q \) is the \( q \)th phase stress–strain tensor is given as:

\[
\tilde{F}_q = \alpha_q \nabla \rho_q (\dot{V}_q + \dot{V}_q \nabla) + \alpha_q \left( \lambda_q - \frac{2}{3} \dot{\gamma}_q \right) \nabla \cdot \dot{V}_q ,
\]

(4)

here \( \mu_q \) and \( \lambda_q \) are the shear and bulk viscosity of phase \( q \), \( \tilde{F}_q \) is an external body force, \( \tilde{F}_{sl,q} \) is a lift force, \( \tilde{F}_{om,q} \) is a virtual mass force, \( \dot{m}_{pq} \) is the interphase momentum exchange coefficient, \( P \) is the pressure shared by all phases and \( \dot{q}_{pq} \) is the interphase velocity.

The momentum equation for solid phase is described as follow:

\[
\frac{\partial (\rho_i \dot{V}_i \rho_i \dot{V}_i)}{\partial t} + \nabla \cdot (\rho_i \dot{V}_i \rho_i \dot{V}_i) = -\alpha_i \nabla P_i - \nabla \cdot (\rho_i \dot{V}_i \rho_i \dot{V}_i) + \alpha_i \dot{g}_i (\tilde{F}_i + \tilde{F}_{sl,s} + \tilde{F}_{om,s}) ,
\]

(5)
where \( P_s \) is the solid pressure, which is composed of a kinetic term and a term due to particle collisions, \( K_{ls} = K_{sl} \) is the momentum exchange coefficient between fluid and solid phase shown as \( l \) and \( s \) respectively, \( N \) is the total number of phases, and \( \vec{F}_l, \vec{F}_{lift,s} \) and \( \vec{F}_{vm,s} \) are different forces exerted on the solids and defined earlier. In the above equations \( \alpha \) is volume fraction and can be defined as follow

\[
v_q = \int_V \alpha q dV.
\]  

(6)

The above partial differential equations are coupled and nonlinear, and can only be solved by numerical methods. In the present research FLUENT 6.3.26 software is used for numerical solution of the governing partial differential equations.

3. Flow conditions and computational grid

In the air drilling, the fluid is injected through drill pipe from top of the well and return to the surface via annulus while conveying cuttings. Return flow which includes two phases, enter the annulus from bottom and exit from top of the well as shown in Fig. 1. Geometrical dimensions of the well and flow conditions are shown in Table 1. It is assumed that all particles are spherical.

The computational grid for the annulus with 0.3 of eccentricity is shown in Fig. 2. A structured grid is used in all of the simulations. The computational domain consists of 35, 125 and 200 nodes in the radial, azimuthal and axial directions, respectively. It was found that with these computational grids, the results are independent of grid size. The convergence criterion was considered \( 1e^{-5} \) for all of the variables.

4. Validation of the model

In order to validate the results, they are compared with the results of Tian and Adewumi (1991) which studied a 2D concentric annulus flow. Fig. 3 compares the particle velocity of present simulation at two different air velocities of 9 and 15 m/s. As shown, there is a good agreement between the results, despite the fact that the velocity of cuttings has small difference with those of Tian and Adewumi (1991). Both results show fast acceleration of particles at the inlet section of annulus which conclude to a constant velocity at the outlet.

Fig. 4 shows a comparison between volume fraction profiles of coarse and fine particles at the outlet of annulus. As shown, particle volume fraction of fine particles is in a good agreement with those of Tian and Adewumi (1991), but for the coarse particles the prediction has a little difference. Generally, at
an equal lifting velocity, volume fraction of coarse particles is more than those of fine particles because coarse particles have larger relaxation time than fine particles. Therefore, their velocity is reduced and the volume fraction is increased compared to the fine particles. At higher axial velocity, drag force exerted on the particles increases and causes less difference between volume fraction of fine and coarse particles. Velocity has the most important effect on the cleanliness of borehole. When air velocity decreases, solid particles are accumulated in the hole due to reduction in drag force and the volume fraction of coarse particles increases.

5. Results

The simulation results are presented for gas–solid two-phase flow in annulus of drilling well with different sizes of cuttings for both concentric and eccentric cases. All results are presented versus dimensionless radius defined as:

$$\sigma = \frac{R - R_1}{R_0 - R_1}$$

In Eq. (7) $R_1$ and $R_0$ are outer diameter of drill pipe and internal diameter of borehole, respectively as shown in Fig. 2. $R$ is the distance between any point of annulus and center of drill pipe.

The effect of solid particles on the air velocity profile at the outlet of annulus is shown in Fig. 5. As shown, in the absence of solid particles, the velocity profile peak is at the middle but tends to the drill pipe side. Because the side area of the borehole is greater than the drill pipe, the friction force is greater over there which results in lower velocity. Presence of solid particles changes the air velocity profile and creates two off-center peaks. This change is due to volume fraction distribution of solids in the annulus as shown in Fig. 6. Volume fraction of solid phase in the zones close to the drill pipe and borehole walls are less than other zones so flow resistance in are lower which allows the air velocity moves faster in these area and creates two peaks.

Fig. 7 shows the velocity profiles of air and solid particles at the outlet of annulus. As shown, particles velocity increases when the inlet air velocity is increased. The velocity profile of solid particles is almost flat, means they move upward with a uniform velocity at major area of the cross section. Particles collision increases the lateral movement of particles and this is the principal reason for flatness of solid velocity profile in comparison to the air velocity profile. The same results are presented by Tian and Adewumi (1991). In order to examine the effect of lower solid mass flow rate, the simulation was performed by considering solid mass flow rate of 1 kg/s. The results showed that the air and solid axial velocity profiles at the outlet of annulus have the same trend.

Fig. 8 shows the effect of drill pipe rotation on the air and particles velocity profiles in a concentric annulus. As shown in this figure, drill pipe rotation has a negligible effect on the air and particles velocity profiles.

Fig. 9 shows the tangential air velocity in a concentric annulus at different rotation of drill pipe. As shown, tangential velocity near the drill pipe wall is maximum due to the no slip condition and decreases sharply to zero away from the wall.

Figs. 10 and 11 show transport velocity and volume fraction of particles at different sectors of an annulus with 0.2 of
Fig. 8 – Effect of drill pipe rotation on the velocity profiles in a concentric annulus.

Fig. 9 – Tangential velocity of air in a concentric annulus.

Fig. 10 – Transport velocity profile of particles at different sectors of annulus with 0.2 of eccentricity.

eccentricity when drill pipe is not rotated. As shown, transport velocity profile of cuttings is almost flat for all sectors with maximum velocity at sector $A-A'$, and minimum velocity at sector $C-C'$. The particles which are at the larger sector of the annulus $(A-A')$ have smaller relaxation time and volume fraction. On the other hand the relaxation time and volume fraction of the particles which are in the smaller sector $(C-C')$ are higher due to lower air velocity in this sector. It can be concluded that in the case of eccentricity in the annulus without drill pipe rotation the particles accumulation increases in the smaller sector of the annulus.

Fig. 12 shows the effect of drill pipe rotation on the velocity profile of air in a vertical annulus with 0.5 eccentricity with and without of solids particles. Rotation of drill pipe produces a quasi-helical flow in the annulus which tends to shift the maximum velocity from the larger sector to the smaller sector of the annulus. This shift in the velocity profile creates more pressure drop in the flow due to more friction. The presence of solid particles results a decrease in gas velocity due to more friction force. As seen, air velocity in the smaller sector is lower than the larger sector, therefore, particles accumulation in the smaller sector is more than the larger sector.

Fig. 13 shows the effects of drill pipe rotation on the volume fraction and particles velocities at the outlet of a vertical annulus with eccentricity of 0.5. As shown, when there is no rotation, eccentricity of the drill pipe makes more accumulation of cuttings in the smaller sector of the annulus. Also, particles velocity in the smaller sector is lower due to the more friction and collision forces; therefore, maximum velocity takes places in the larger sector. Rotation of drill pipe shifts the maximum point in the velocity profile from larger sector to the smaller one by producing a rotational flow which results less accumulation of particles in the smaller sector. Increasing angular velocity of drill pipe increases this effect. Therefore, one can conclude that in the case of eccentricity, increasing the drill pipe rotation can improve the cuttings transport in the annulus and prevent drill pipe stickness.

Fig. 14 shows the effect of drill pipe rotation on the pressure drop. As shown, pressure drop slightly increases with increasing rotation of the drill pipe. This effect is due to the increasing friction between particles and walls and between particles themselves.

Fig. 11 – Volume fraction profile of particles at different sectors of annulus with 0.2 of eccentricity.
Effect of eccentricity on the pressure loss is shown in Fig. 15. As shown, by increasing eccentricity pressure drop also increases. When there is eccentricity, particles tend to move to accumulate in the smaller sector of the annulus which results in more contact between them and also between them and wall, therefore, pressure loss increases. It is recommended to use casing stabilizer to prevent eccentricity of drill pipe.
Fig. 13 – Effects of drill pipe rotation on the particle volume fraction (a, c, and e) and particles velocities (b, d, and f) profiles for a vertical annulus with eccentricity of 0.5.
software. A three-dimensional approach was used in order to investigate the effect of drill pipe rotation and eccentricity on the air and particles velocity profiles and particles volume fraction in the annulus.

It was found that presence of solid particles in a concentric annulus changes the air velocity profile significantly by creating two off-center peaks velocity close to the wall surfaces. The particle velocity profile is almost flat. Particle volume fraction in the annulus is changed radially and it has two peaks at both sides of annulus centerline. Rotation of drill pipe produces a quasi-helical flow in the annulus which improves cuttings transport. Drill pipe rotation increases pressure drop due to increase in particles collisions and also collision with the wall.

When there is eccentricity, accumulation of particles in the smaller sector increases and this result in more collision between particles with each other and between particles and walls which cause an increase in pressure drop. It is recommended to use casing stabilizer to prevent eccentricity in drill pipe.

References


6. Summary and conclusion

In this paper gas–solid two-phase flow in the annular space of a drilling well was studied using two-fluid model of FLUENT.